crab cavities for the LHC Upgrade

Frank Zimmermann

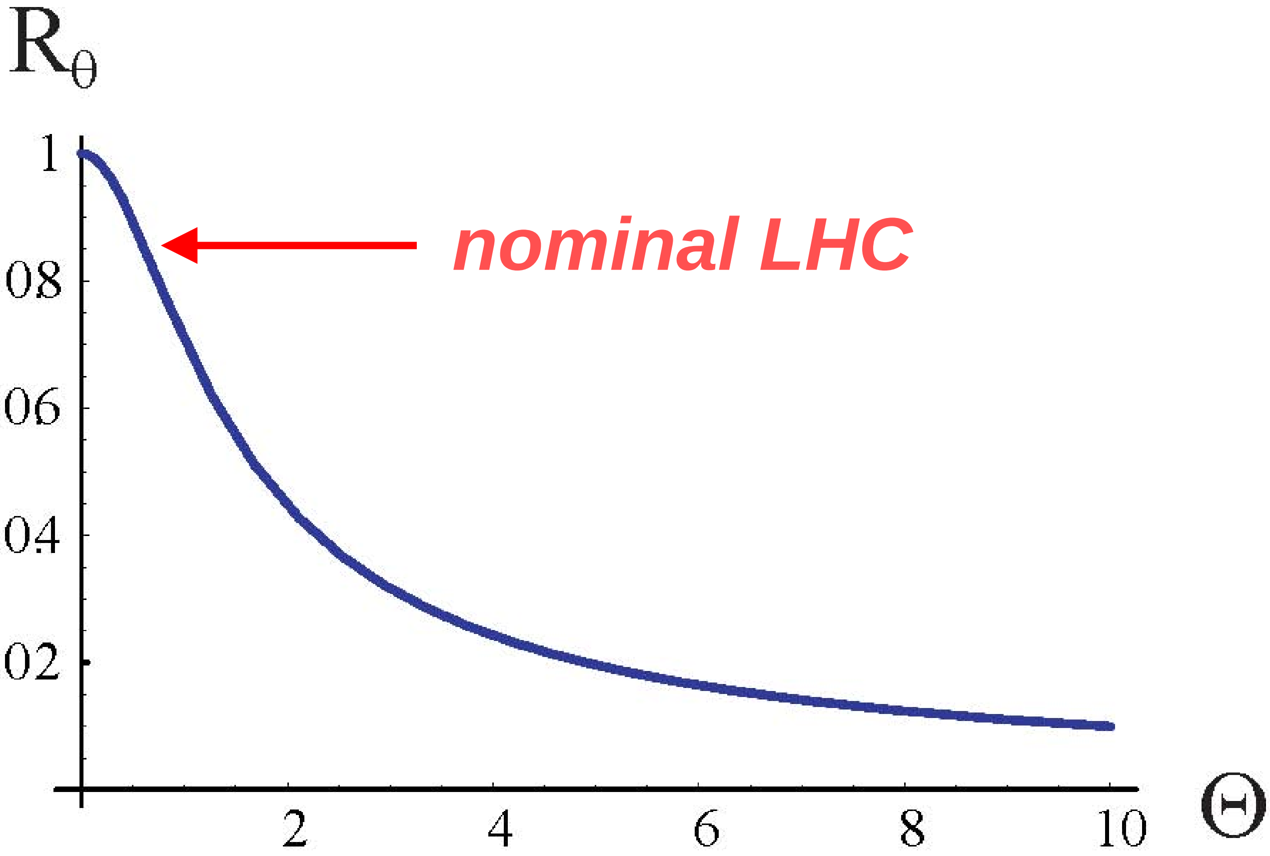
Thanks to
Kazunori Akai, John Byrd, Kazuhito Ohmi,
Katsunobu Oide, Francesco Ruggiero,
Joachim Tuckmantel,Tanaji Sen

(1) need for beam-beam compensation

- **nominal LHC parameters are challenging & “at the edge”:**
  - ~20% geometric luminosity loss from crossing angle
  - chaotic particle trajectories at 4-6σ due to long-range beam-beam effects
- **if we increase #bunches or bunch charge, or reduce β^*:**
  - long-range beam-beam effects require larger crossing angle
  - but geometric luminosity loss would be inacceptable!

$$R_\theta = \frac{1}{\sqrt{1+\Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x}$$ Piwinski angle

luminosity reduction factor



to boost LHC performance further various approaches have been proposed:

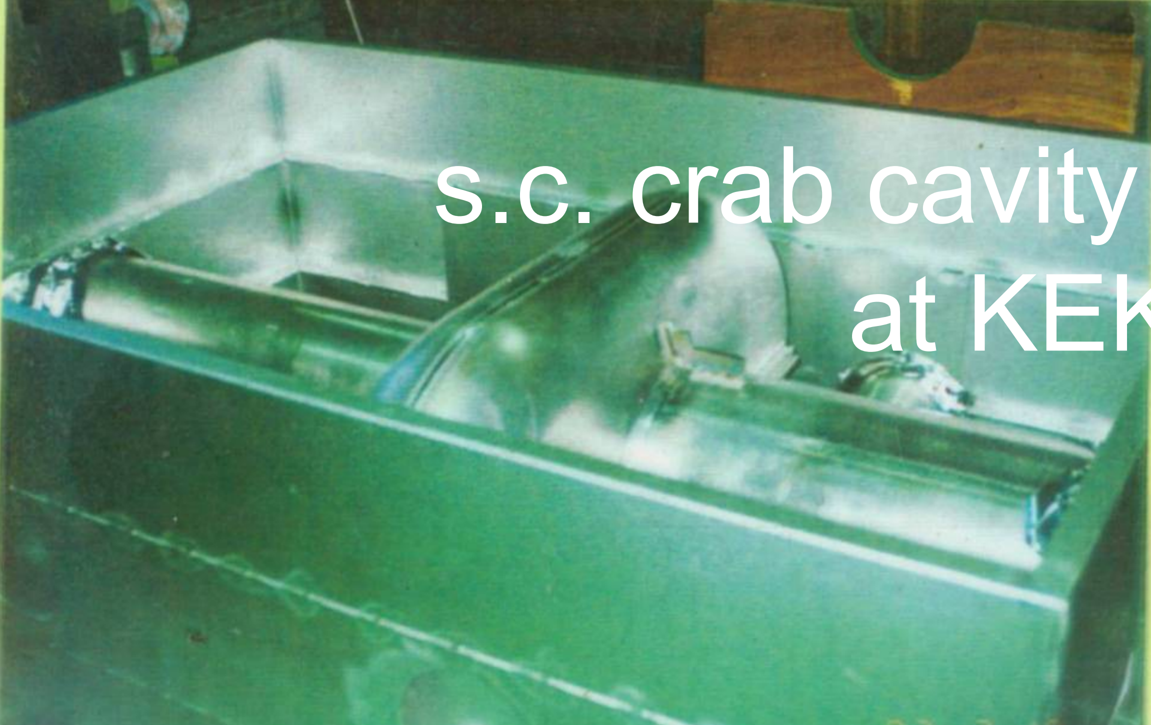
1) **increase crossing angle AND reduce bunch length**
   (higher-frequency rf & reduced longitudinal emittance)
   [J. Gareyte; J. Tuckmantel, HHH-20004]

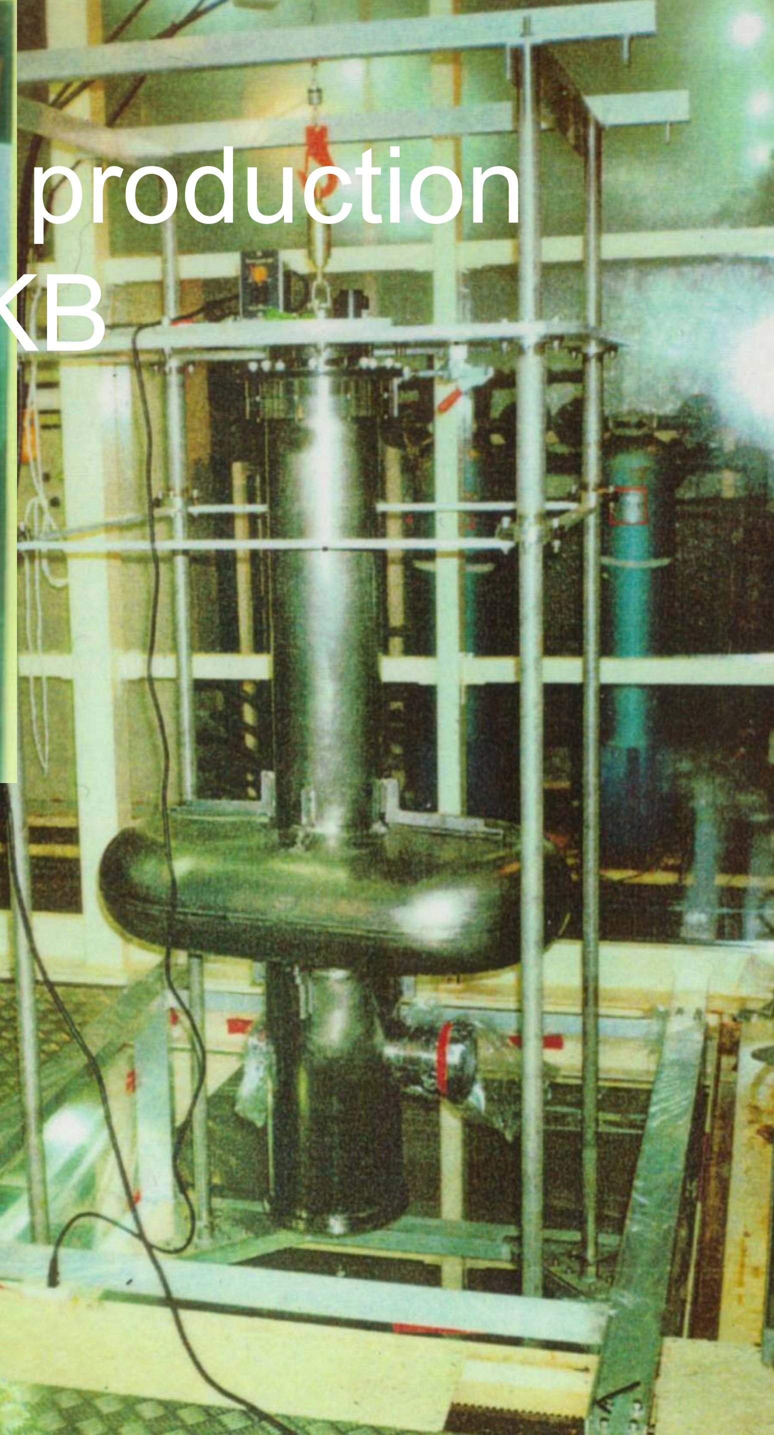
2) **reduce crossing angle & apply “wire” compensation**
   [J.-P. Koutchouk]

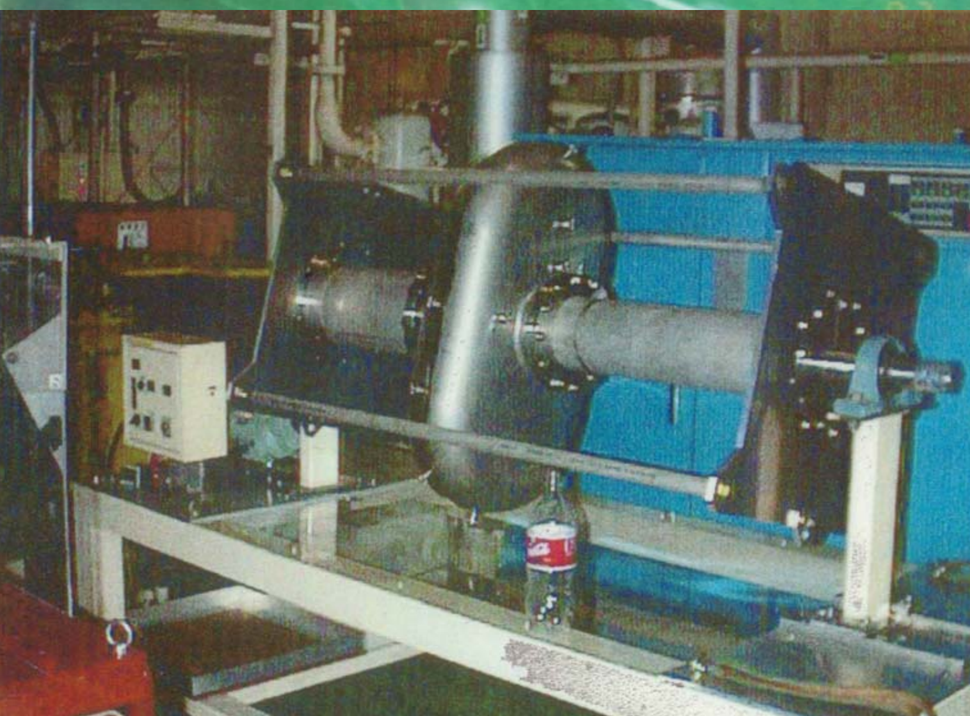
3) **crab cavities → large crossing angles w/o luminosity loss**
   [R. Palmer, 1988; K.~Oide, K. Yokoya, 1989; KEKB 2006]

4) **collide long intense bunches with large crossing angle**
   [F. Ruggiero, F. Zimmermann, ~2002]

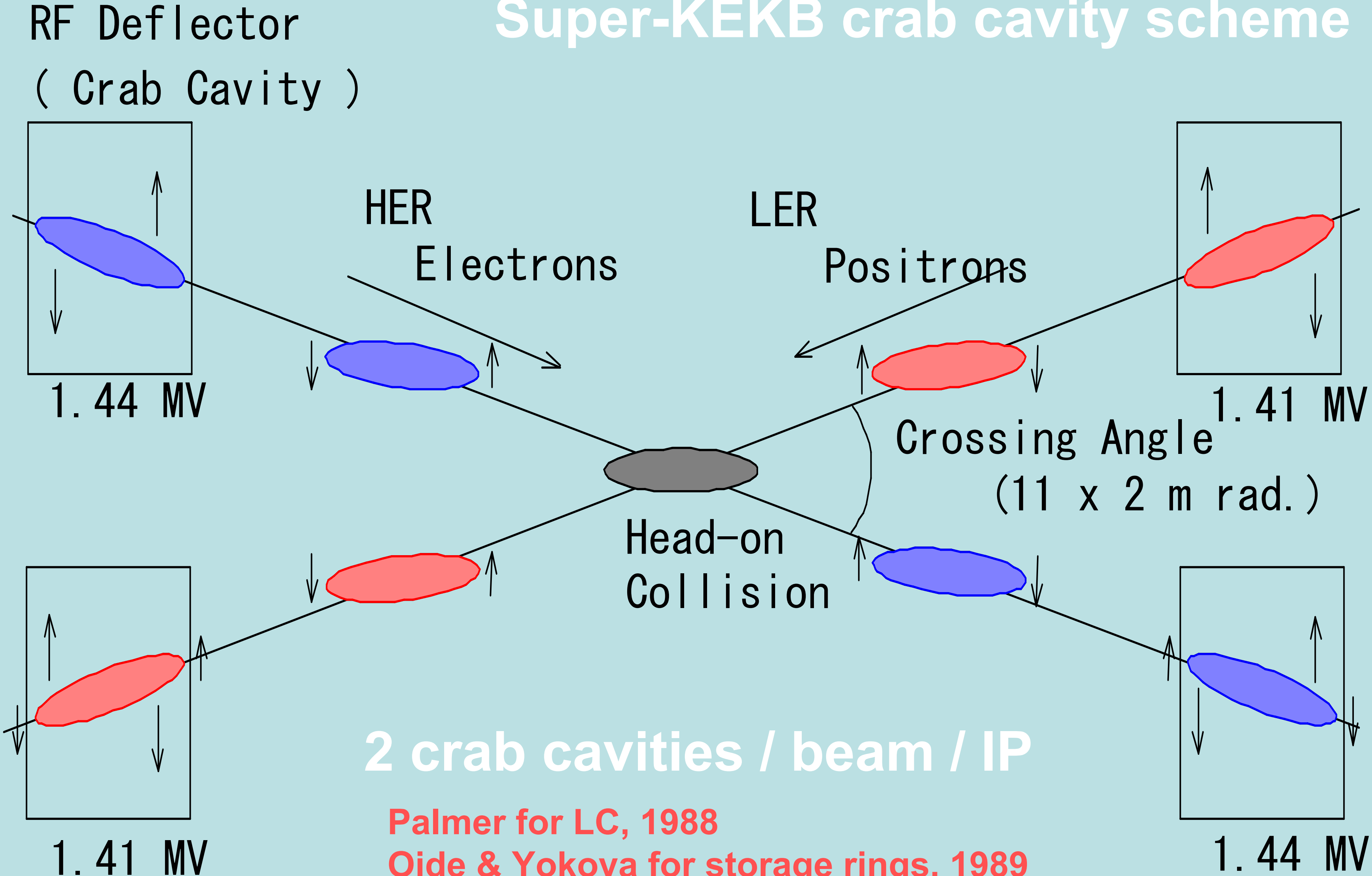
s.c. crab cavity production at KEKB





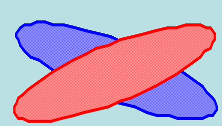


Super-KEKB crab cavity scheme



2 crab cavities / beam / IP

Palmer for LC, 1988
Oide & Yokoya for storage rings, 1989



first crab cavities will be installed at KEKB in early 2006

history of s.c. crab cavity developments

- CERN/Karlsruhe sc deflecting cavity for separating the kaon beam, 1970's, 2.86 GHz*
- Cornell 1.5 GHz crab cavity 1/3 scale models 1991*
- KEK 500 MHz crab cavity with extreme polarization, 1993-present, for 1-2 A current, 5-7 mm bunch length
- FNAL CKM deflecting cavity, 2000-present*
- KEK 2003 new crab cavity design for Super-KEKB, 10 A beam current, 3 mm bunch length, more heavily damped (coaxial & waveguide)
- Daresbury is studying crab cavities for ILC, 2005
- Cornell and LBNL are interested in developing crab cavities for Super-LHC

*H. Padamsee, Daresbury Crab Cavity Meeting, April 2004

bunch shortening rf voltage:

$$V_{rf} \approx \left[\frac{\varepsilon_{\|,rms}^{2} c^{3} C \eta}{E_0 \, 2\pi f_{rf}} \right] \frac{1}{\sigma_z^4} \approx \left[\frac{\varepsilon_{\|,rms}^{2} c^{3} C \eta}{E_0 \, 2\pi f_{rf}} \right] \frac{\theta_c^4}{0.7^4 \, 16 \sigma_x^{*4}}$$

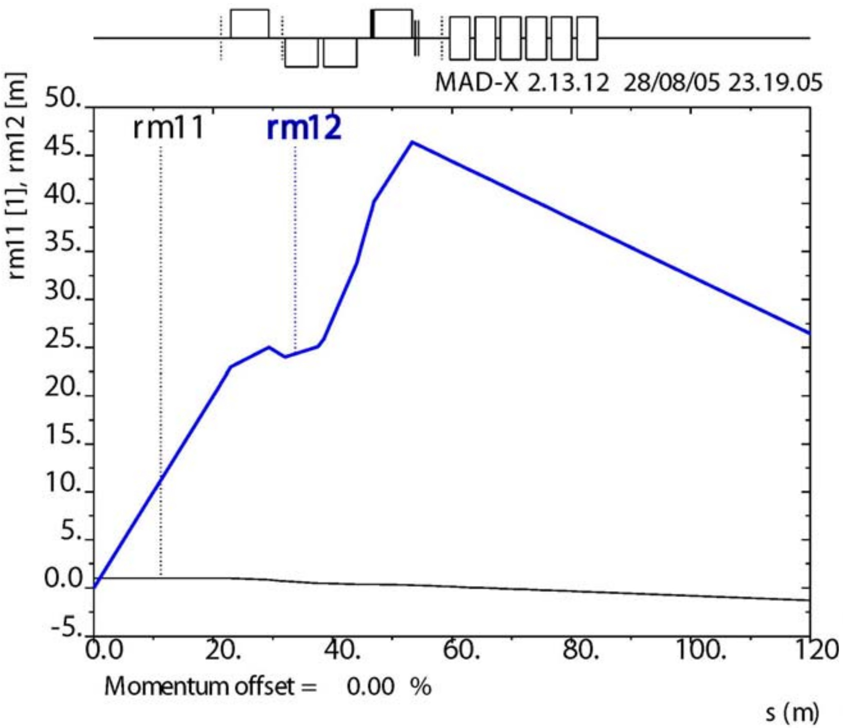
unfavorable scaling as 4th power of crossing angle and inverse 4th power of IP beam size; can be decreased by reducing the longitudinal emittance; inversely proportional to rf frequency

crab cavity rf voltage:

$$V_{crab} = \frac{c E_0 \tan(\theta_c / 2)}{e 2\pi f_{rf} R_{12}} \approx \frac{c E_0}{e 4\pi f_{rf} R_{12}} \theta_c$$

proportional to crossing angle & independent of IP beam size; scales with $1/R_{12}$; also inversely proportional to rf frequency

R12 & R22(R11) from MAD

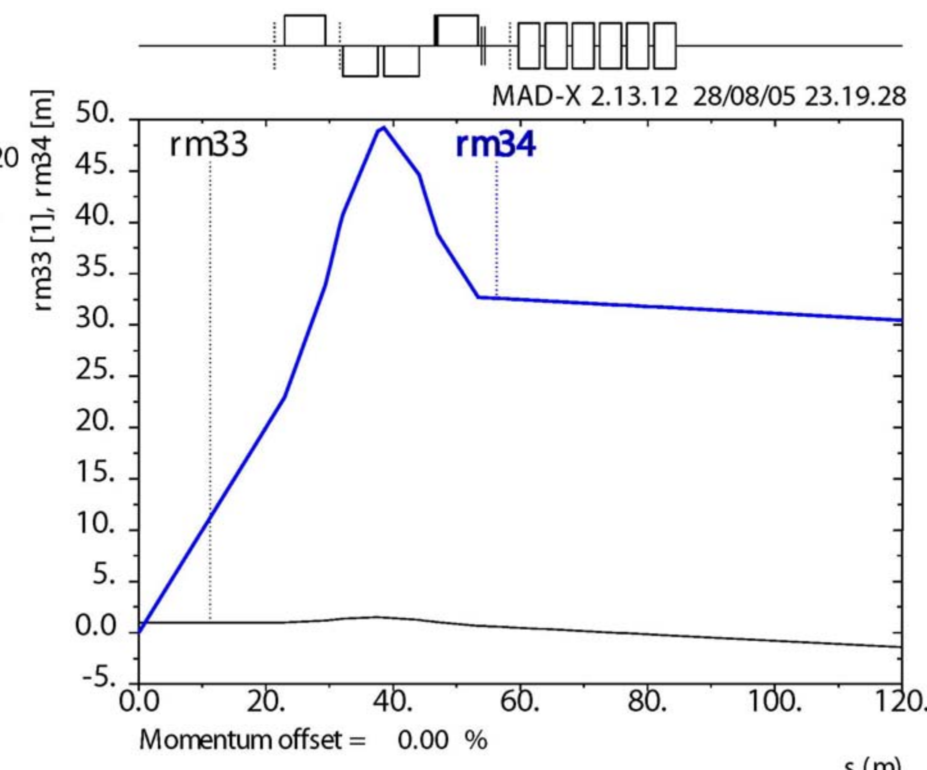


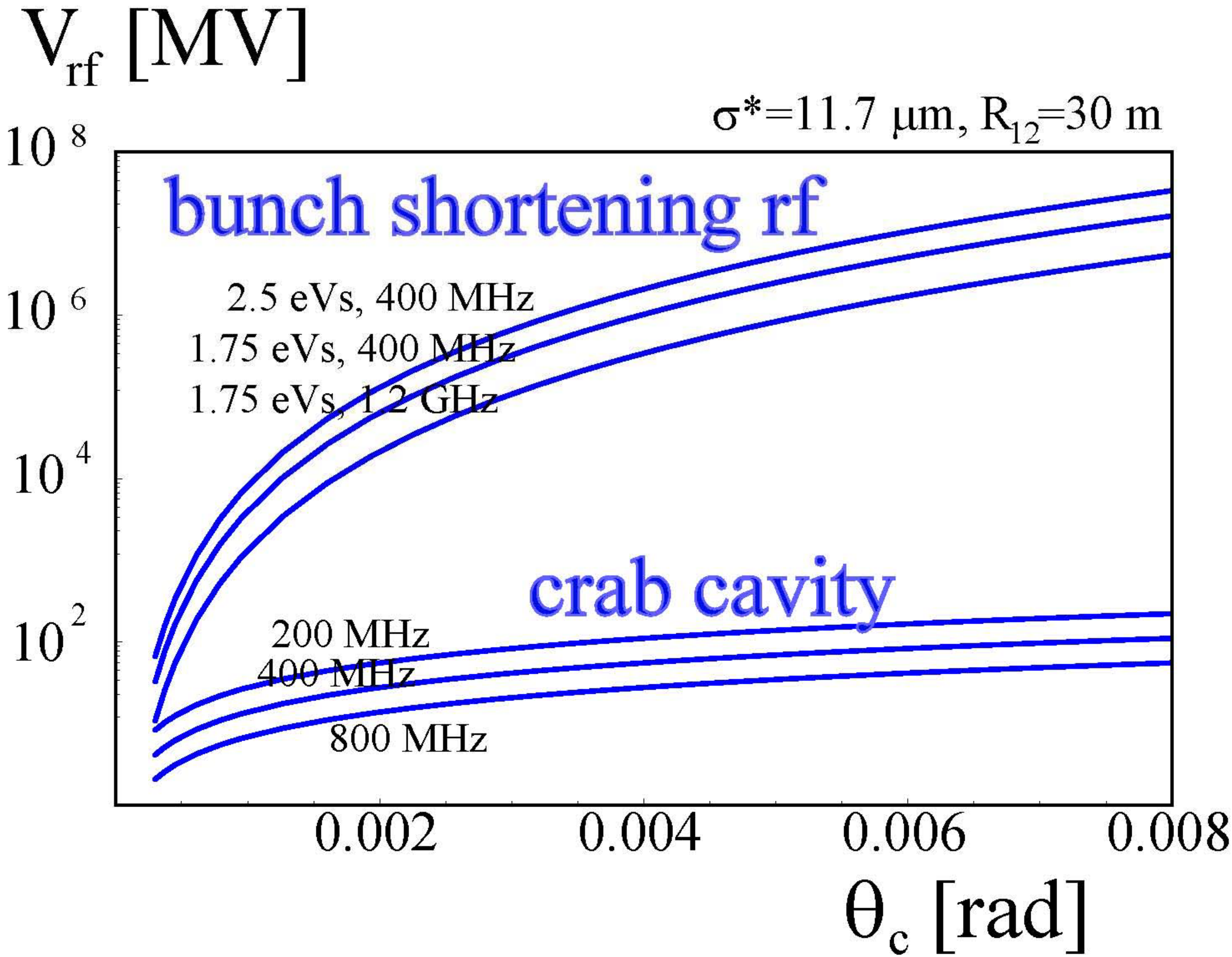
nominal LHC optics

$|R_{12,34}|$~30-45 m

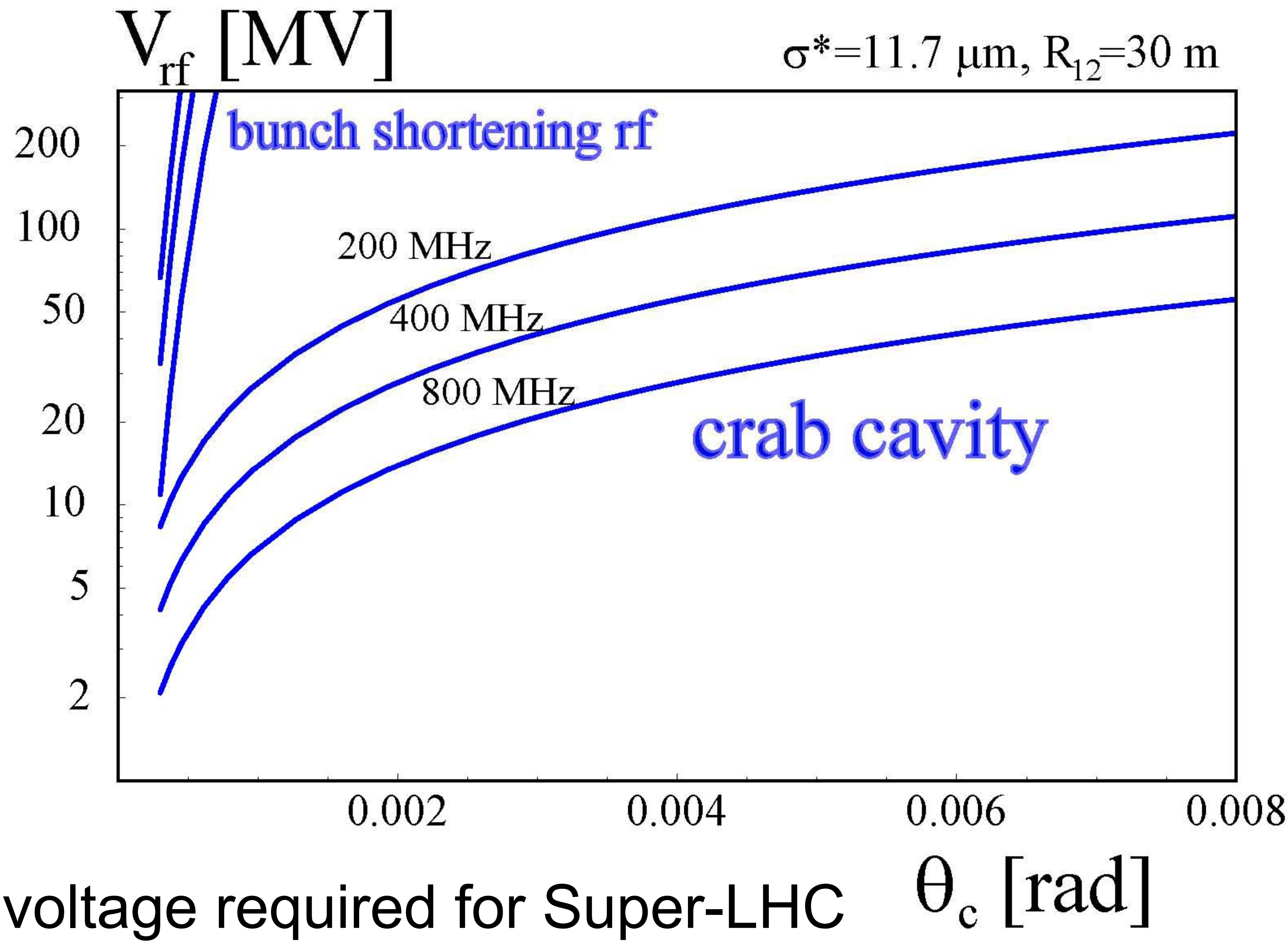
$|R_{22,44}|$~1

(from crab cavity to IP)





V_{rf} [MV]
σ*=11.7 μm, R_{12}=30 m
10^8
10^6
10^4
10^2
bunch shortening rf
2.5 eVs, 400 MHz
1.75 eVs, 400 MHz
1.75 eVs, 1.2 GHz
crab cavity
200 MHz
400 MHz
800 MHz
0.002
0.004
0.006
0.008
θ_c [rad]



voltage required for Super-LHC

crab cavity voltage for different θ_c's & rf frequencies

crossing angle	0.3 mrad	1 mrad	8 mrad
800 MHz	2.1 MV	7.0 MV	56 MV
400 MHz	4.2 MV	13.9 MV	111 MV
200 MHz	8.4 MV	27.9 MV	223 MV

*800 MHz would be too high for nominal LHC bunch length

tolerance on R22

$$\Delta\theta_c\left(z\right) \cong \frac{R_{22}}{R_{12}}\left(\frac{\theta_c}{2}z\right)$$

z-dependent additional crossing angle

$$\frac{\Delta\theta_c\left(2\sigma_z\right)\sigma_z}{2\sigma_x^*} = \frac{R_{22}}{R_{12}}\frac{\theta_c\sigma_z^2}{\sigma_x^*} << 1$$

corresponding Piwinski angle should be small

$$R_{22} << \frac{R_{12}\sigma_x^*}{\theta_c\sigma_z^2} \approx 60 \,|$$

not a problem

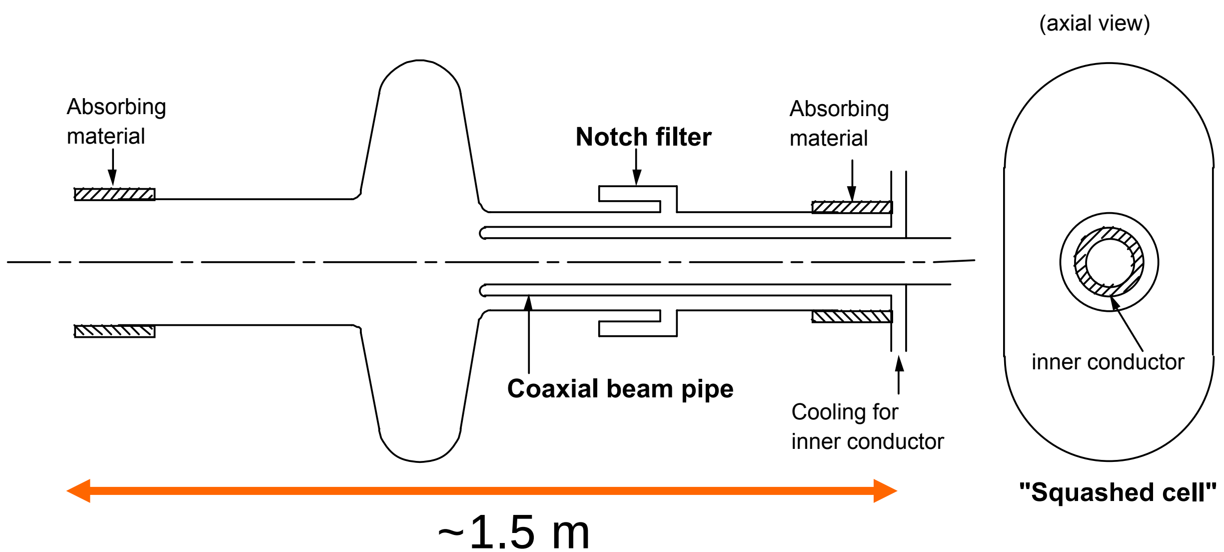
[for θ_c=1 mrad, σ_x=12 mm, R_{12}=30 m, σ_z=7.55 cm]

K. Ohmi, HHH-2004

~1.5 MV@500 MHz

KEKB crab cavity

- Squashed cell operating in TM2-1-0 (x-y-z)
- Coaxial coupler is used as a beam pipe
- Designed for B-factories (1〜2A)



Squashed Crab cavity for B-factories

(K. Akai et al., Proc. B-factories, SLAC-400 p.181 (1992).)

Courtesy K. Akai

longitudinal space & crab frequency

longitudinal space required for crab cavities scales roughly linearly with crab voltage; desired crab voltage depends on rf frequency); achievable peak field also depends on rf frequency; 2 MV ~ 1.5 m, 20 MV ~ 15 m

frequency must be compatible with bunch spacing; wavelength must be large compared with bunch length;

$$\Delta x'(z) \cong \frac{1}{R_{12}}\left(\frac{\theta_c}{2} z - \frac{\theta_c}{2}\frac{1}{6}\frac{c^2}{\omega_{rf}^2} z^3\right) + \ldots \qquad \omega_{rf} < \frac{\sqrt{6}c}{2\sigma_z} \cong 2\pi(775\,\mathrm{MHz})$$

400 MHz reasonable

noise

- amplitude noise introduces small crossing angle; e.g., 1% jitter → 1%θ_c/2 cross. angle – tolerance <0.1% jitter from emittance growth
- phase noise causes beam-beam offset; tolerance on LHC IP offset random variation Δx_{max}~10 nm, from emittance growth

→ tight tolerance on left-right crab phase and on crab-main-rf phase differences

$$\Delta\phi_{crab} \leq \frac{\Delta x_{max} 4\pi}{\lambda_{rf}\theta_c}$$

$\Delta\phi$ <0.012° (Δt<0.08 ps) at θ_c=1 mrad & 400 MHz
$\Delta\phi$ <0.04° (Δt<0.28 ps) at θ_c=0.3 mrad & 400 MHz

comparison of timing tolerance with others

	KEKB	Super-KEKB	ILC	Super-LHC
σ_x^*	100 μm	70 μm	0.24 μm	11 μm
θ_c	+/- 11 mrad	+/-15 mrad	+/-5 mrad	+/- 0.5 mrad
Δt	6 ps	3 ps	**0.03 ps**	**0.08 ps**

$\underbrace{\hspace{6cm}}$

IP offset of 0.2 σ_x^*

IP offset of 0.001 $\boldsymbol{\sigma_x}^*$
~10 nm

→ *not more difficult than ILC crab cavity*

p emittance growth due to random offsets

$$\frac{\Delta\varepsilon}{\Delta t} \approx \frac{n_{IP} 8\pi^2 (\Delta x)^2_{rms} \xi^2_{HO} f_{rev}}{\beta^*}$$

emittance growth from turn-by-turn random collision offsets Δx

SuperLHC: $\beta^*_{x,y}$=0.25 m, n_{IP}=2, ξ_{HO}=0.005, γ=7500, $\gamma\varepsilon$=3.75 μm

requiring less than 10%/hr emittance growth

$\longrightarrow$ $\Delta x_{rms} < 8$ nm ~ $10^{-3}\sigma^*$

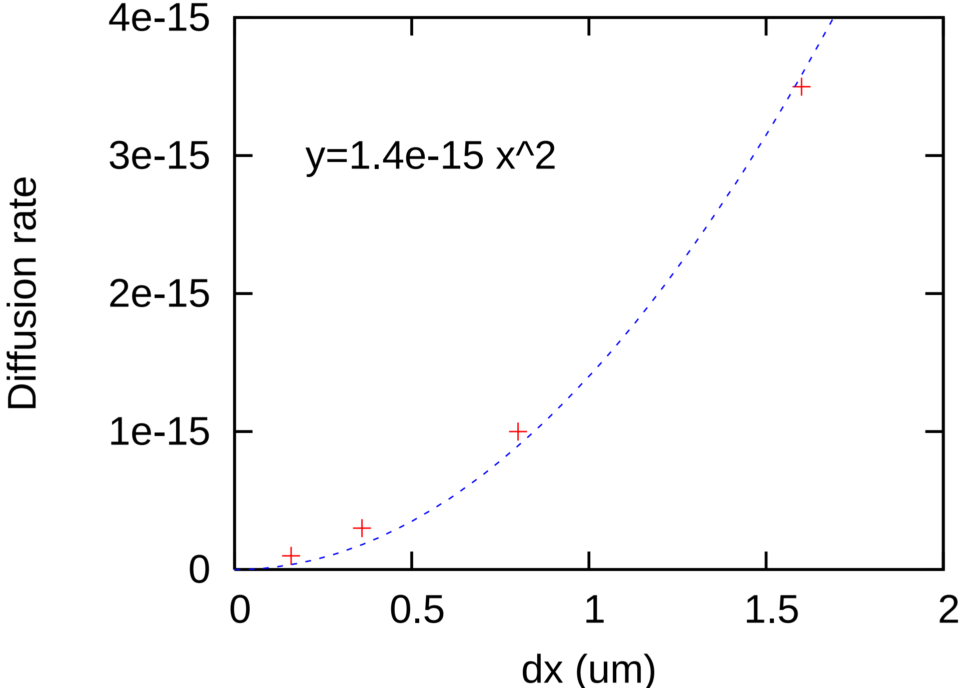
$\Delta\phi < 0.008^o$ at θ_c=1 mrad & 400 MHz

$\Delta\phi < 0.027^o$ at θ_c=0.3 mrad & 400 MHz

K. Ohmi, HHH-2004

diffusion rate from strong-strong simulation with BBSS for nominal LHC

- $\sigma_x^2 = \sigma_{x0}^2 + Dt$ t: turn
- $D \sim 1.4 \times 10^{-15}\ \Delta x[\mu m]^2$



$\delta z =$ 0   0.005   0.01

K. Ohmi, HHH-2004

tolerance from Ohmi san's strong-strong simulation for nominal LHC

- For $\Delta x=1.6\ \mu m$ ($\delta\phi=5$ degree) and $\tau=100$, $D\sim1.4\times10^{-15}\ \Delta x[\mu m]^2$, where $\sigma_x^{\ 2}=\sigma_{x0}^{\ 2}+Dt$, t: turn.
- Tolerance is $\Delta x=0.016\ \mu m$, $\Delta\phi= 0.05$ degree for $\tau=100$, and $\Delta x=0.0016\ \mu m$, 0.005 degree for $\tau=1$, for luminosity life time ~ 1 day

slightly worse than my simple estimate!?

for 300 μrad crossing angle and 400 MHz

analytic theory of beam-beam diffusion

(T. Sen et al., PRL77, 1051 (1996)
M.P.Zorzano et al., EPAC2000)

- Diffusion rate due to offset noise. (round beam)

$$D(J_x) = \frac{(C\sigma|\delta x|)^2}{8-4/\tau} \sum_{k=0}^{\infty} \frac{\sinh\theta(2k+1)^2 G_k^2(a)}{\cosh\theta - \cos\left[2\pi(2k+1)\nu_x\right]}$$

$$G_k = \frac{\sqrt{a}}{\sigma}\left[U'_{k+1} + U'_k\right] + \frac{1}{\sqrt{a}\sigma}\left[(k+1)U_{k+1} - kU_k\right]$$

$$U_k(a) = \int_0^a \frac{1}{w}\left[\delta_{0k} - (2-\delta_{0k})(-1)^k e^{-w} I_k(w)\right] dw$$

$$\theta = -\ln(1 - 1/\tau)$$

$$C = \frac{N_p r_p}{\gamma_p} \qquad a = \frac{\beta^* J_x}{2\sigma^2}$$

K. Ohmi, HHH-2004

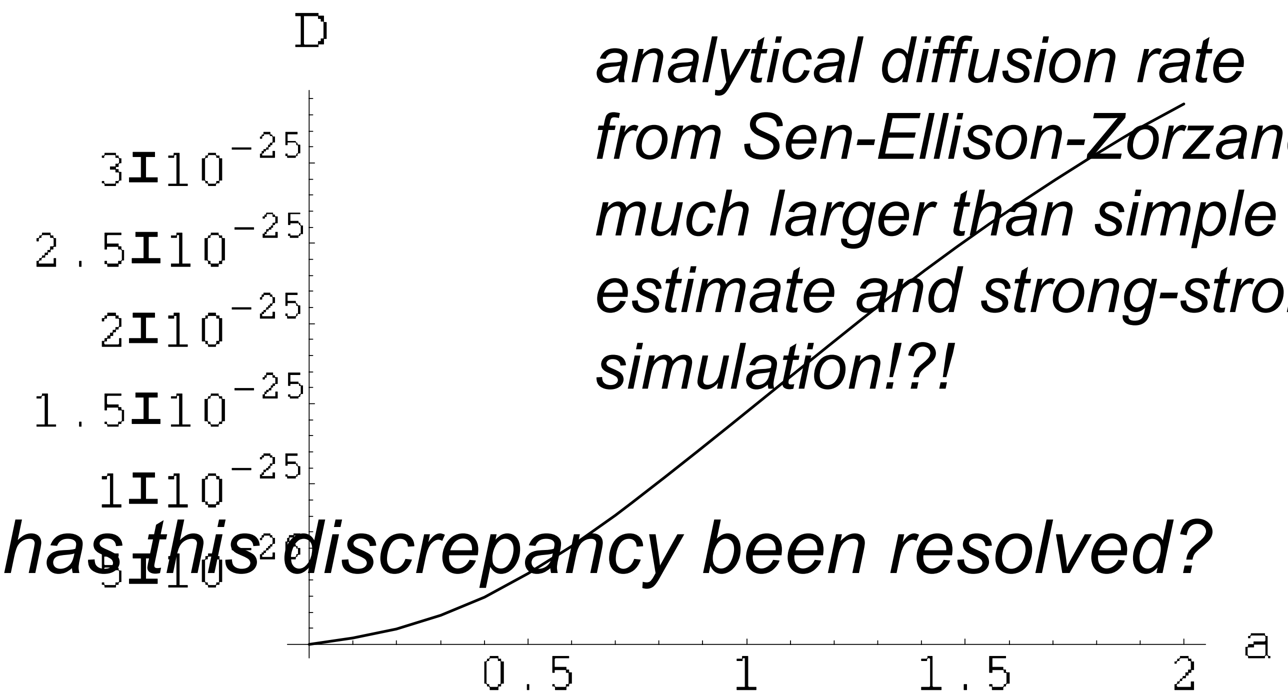
K. Ohmi, HHH-2004

comparison with the simulation

- $D(a=1)=<\Delta J^2>=1.5\text{x}10^{-25}$ m^2/turn
- $D(sim)=(\sigma-\sigma_0{}^2)^2/\beta^2 = 10^{-28}$ m^2/turn

"need to check"

3 orders of magnitude discrepancy!



analytical diffusion rate from Sen-Ellison-Zorzano much larger than simple estimate and strong-strong simulation!?!

has this discrepancy been resolved?

in addition to beam-beam offset, also the direct dipole kicks from random crab cavity phase jitter induce emittance growth

(J. Tuckmantel)

my estimate:

$$\frac{\Delta\varepsilon}{\Delta t} \approx \frac{f_{rev}}{\beta^*}\left(\frac{c\,\theta_c}{4\pi f_{crab}}\Delta\phi_{crab}\right)^2$$

example:

$$\beta^* \approx 0.25\,\mathrm{m},\ f_{crab} = 400\,\mathrm{MHz.},\ \Delta\phi_{crab} \approx 0.01\,\mathrm{mrad},\ \theta_c \approx 1\,\mathrm{mrad}$$

(6x10^{-4} °)

$$\longrightarrow \quad \frac{1}{\varepsilon}\frac{\Delta\varepsilon}{\Delta t} \approx 11\% / hr$$

~0.004 ps!

this effect likely requires transverse feedback, head-tail damping, or other scheme to suppress the dipole motion, or it can eliminate the idea altogether

impedance of crab cavities

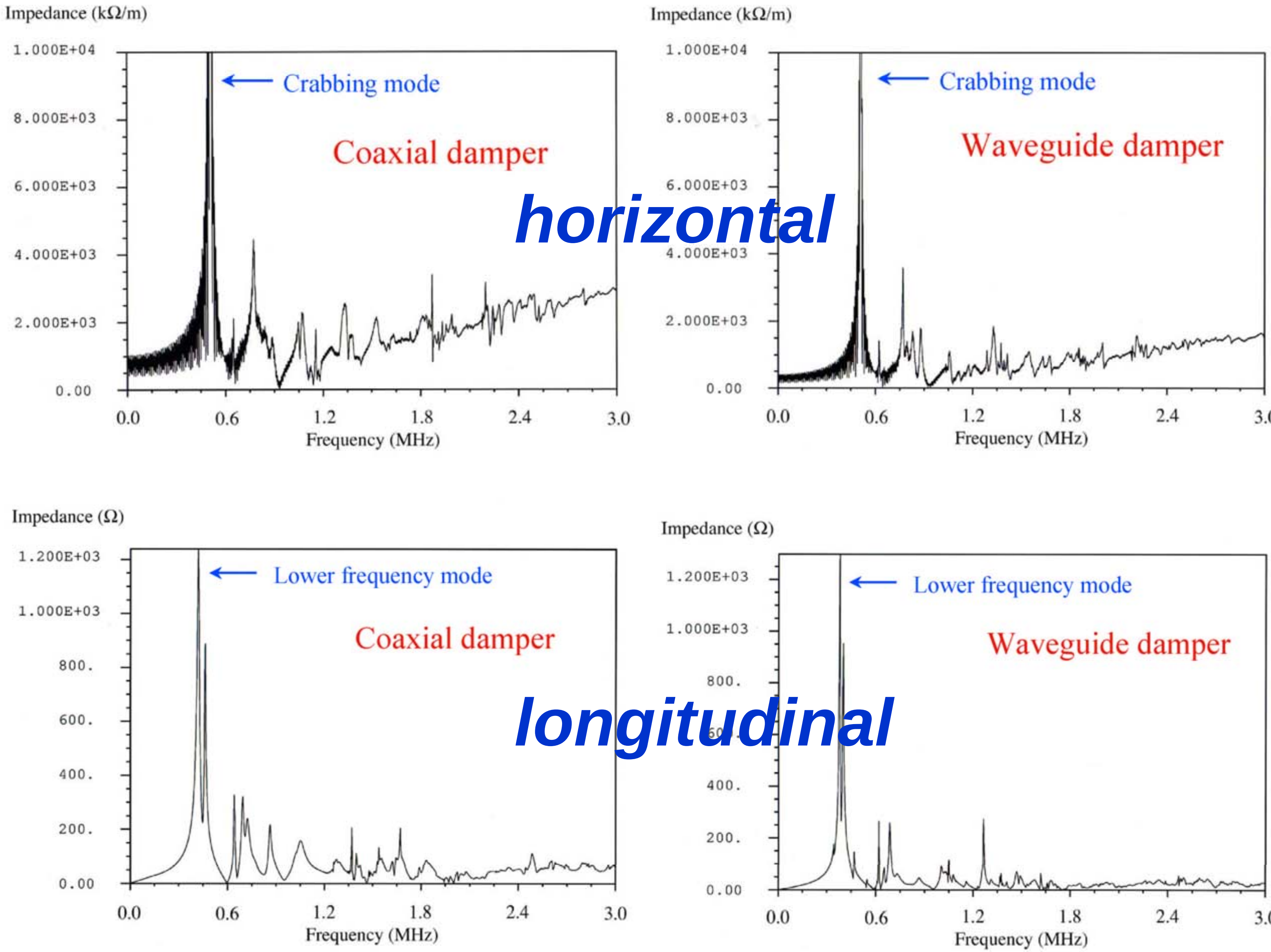
transverse impedance is an issue
due to large beta function

rise time due to 1 crab cavity
=
rise time from ~10 normal rf cavities
with the same voltage

K. Akai

Impedance of Super-KEKB Crab Cavity Design

K. Akai



merits of crab cavities

- practical demonstration at KEKB in early 2006
- avoids geometric luminosity loss, allowing for large crossing angles (no long-range beam-beam effect)
- potential of boosting the beam-beam tune shift (factor 2-3 predicted for KEKB)

challenges & proposed plans

- design & prototype of Super-LHC crab cavity (Cornell and LBNL are interested)
- demonstration that noise-induced emittance growth is acceptable for hadron colliders (installation & experiment at RHIC?)